Chapter 2

Power Optimization for Wireless Sensor Networks

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1. Introduction

Wireless Sensor Network (WSN) is a denomination that covers a lot of variations in compositions and deployment. A typical sensor network consists of a large number of low cost, low power distributed devices, called nodes, deployed in the environment being sensed and controlled (Stankovic et al., 2003). In other words, this kind of network is composed of a huge number of tiny nodes able to communicate with each other that can be used to monitor hazardous and inaccessible areas. Thus, each node consists of processor, memory, wireless antenna, battery and the sensor itself. Nodes can sense scalars from the environment such as temperature, acoustic and light, but may also process and transmit them by radio. The network can be classified as homogeneous or heterogeneous, which would mean that some specific nodes present special hardware or software configuration, but even in homogeneous networks, to collect, store and process data from the WSN's nodes, a special node, called Base Station (BS), is necessary.

Most of the currently adopted technologies for WSNs are based on low-cost processors, resulting in limited energy budget and restricted memory space. In many applications, it is expected that the sensor node last for a long time because in most of the cases these networks are used in remote areas and recharging and/or replacing power supply units is considered difficult or prohibitive due to hazardous and inaccessible places where they are supposed to operate. Further, due to the availability of cheap hardware and various possibilities for the radio communication frequency, numerous topologies for WSN can be adopted (Akyildiz, 2002; Ilyas & Mahgoub, 2005; Oliver & Fohler, 2010).

As previously mentioned, the nodes in these networks are usually inexpensive and therefore WSNs may be composed of a huge number of sensor nodes, which themselves are deployed inside and/or around the phenomenon that one desires to monitor. Not necessarily the sensor node's geographic position is previously known in all adoptions,

because, when the nodes need to work in hazardous or inaccessible areas, it might be impossible to avoid their random deployment. Thus, if this type of application is adopted, the use protocols and approaches that can self-organize and self-optimize energy consumption of a large number of nodes that cooperate in order to achieve a global goal, becomes necessary (Akyildiz, 2002). Summarizing, WSN are desired to present the following characteristics (Ilyas & Mahgoub, 2005):

- Self-organization;
- Short range wireless communication and multi-hop routing;
- Large number of nodes and cooperative efforts between WSN nodes;
- Different WSN topologies, which frequently change due to battery depletion and node faults;
- Constrained resources such as energy budget, processing and memory.

The characteristics above and the capacity of interaction with the environment distinguish WSNs from other ad-hoc wireless networks. WSNs, due to the scarce software and hardware resources, are application oriented; thus, WSN applications are developed focusing on a specific problem's solution. The collaborative efforts between nodes are necessary to the correctly use the WSN's resources, this effort can also increase the WSN's lifetime (Stankovic et al., 2003; Hadim & Mohamed, 2006).

It is important to highlight that the strategy of deploying a large number of unreliable nodes presents advantages when compared with deploying few expensive but very reliable nodes (Ilyas & Mahgoub, 2005). These advantages are listed below:

- Larger spatial resolution;
- Higher fault tolerant degree achieved throughout distributed techniques;
- More uniform coverage;
- Ease of deployment;
- Reduced energy consumption;
- Increased network lifetime.

WSNs present a high degree of environmental interaction, depending on where sensor nodes are deployed, implicit and explicit temporal restrictions apply. In this context, data freshness is an important concept that dictates how long a sensed scalar can be considered useful and when it can be discarded. In the following example, the information gathered by a security application based on WSN technology, identifies any person who enters into a certain area of the building in a certain time, all data that exceeds this time limit, is not useful. Despite having time constraints, due to the high node density, non-determinism, noise and constrained WSN resources, it becomes extremely difficult to guarantee real-time properties (Stankovic et al., 2003). Therefore, these special constraints impose that no hard deadlines are considered for WSN application. Consequently, critical real-time systems are out of scope for this kind of network (Koubaa et al., 2009; Oliver & Fohler, 2010).

WSN can be considered an innovative paradigm, which permits the emergence of several new monitoring applications, but introduces challenges intrinsic to this technology. Some of

these challenges are (Akyildiz, 2002; Stankovic et al., 2003; Molla & Ahamed, 2006; Yick et al., 2008; Ilyas & Mahgoub, 2005):

- *Paradigm change:* WSN are basically deployed in order to collect scalars from the environment and support control applications. The WSN application must sense the environment and, sometimes, act in one way or the other on the environment. Thus, it is considered critical to obtain a cooperative behaviour of thousands of sensor nodes where the data from just one node may not be important. The sensor nodes do not have a permanent identification address, due to the fact that generally messages are not sent to a specific node but to a space or area (based on the message's content). Users can be interested in the information about a specific monitoring area, thus the sensed data from a specific node may not be important, representing the data centric approach in WSNs. The need of physical environment interaction also implies important differences between WSNs and ordinary ad-hoc networks, thus classical distributed system techniques are not applicable to WSNs. Real-time requirements, noise, high fault occurrence and non determinism also impose a new group of approaches that must deal with these constraints (Molla & Ahamed, 2006).
- *Resource Constraints:* As noted above, WSNs face severe resource constraints. The main resource constraints are: limited energy budget, restricted CPU clock, restricted memory as well as network bandwidth. These characteristics impose the application of new solutions. The fact that WSN topologies are composed of a huge number of nodes represents a new issue that had not been considered in simple ad-hoc networks. For instance, trade-off approaches that aim at guaranteeing energetic economy and real-time characteristics became necessary (Yick et al., 2008).
- *Unpredictability:* There are many uncertainties that may affect a WSN. Firstly, WSN are deployed in environments with multiple uncontrollable events. Secondly, wireless communication is sensitive to noise; data lost due to radio interference and several physical errors is common to networks employed in harsh environments. Thirdly, nodes are not individually dependable. Further, it is not always possible to properly calibrate the nodes before employment; routing structures such as paths and the connectivity can be dynamically added or excluded during the WSN time of functioning. The addition or removal of nodes might be necessary due to permanent faults or battery depletion. Additionally, the energy level in some node can significantly vary even during the initial deployment. Last, the nodes might be physically removed due to environment causes or intentional controlling, thus a network restructuring must would be necessary.
- *Self-*:* One of the biggest challenges is to create the WSN's vision in the network application layer. Due to the fact that WSNs are deployed to operate with few or none human intervention, self-* characteristics like self-organization, self-optimization and self-healing become necessary (Huebscher & McCann, 2008; Oliver & Fohler, 2010). These characteristics are easily listed as challenge, however are extremely difficult to achieve.

- *High scale/density:* There are several WSN approaches that consider a large number of nodes in order to overcome hardware or software faults, thus there is a minimum number of nodes that is necessary to guarantee the WSN's service. The main challenges include: the processing of this large number of generated data, the assurance that the particular WSN requires the minimum desirable density, and the development of solutions that require the lowest density and energy consumption in order to maximize the WSN's lifetime. A WSN based on a large number of nodes that are deployed in large areas is considered a large-scale system. Due to its characteristics, these systems are subject to faults, noise, which sometimes can be caused by the WSN itself, and other uncertainties. Moreover, when a WSN is deployed, it might be self-operational and present self-maintenance, due to the fact that human intervention is sometimes very expensive or even impossible. Therefore, all these characteristics impose several conflicting goals. These challenges can be increased by the technology scaling, where the industry's minimization tendency (Akyildiz et al., 2008).
- *Real-time:* WSNs operate in the real world, thus real-time features are necessary to guarantee the correct functionality. These systems present implicit real-time constraints. The response time of its tasks is also important, thus the system tasks must be finished as fast as possible. Several WSNs present explicit real-time constraints. For example, a structural monitoring application imposes explicit deadlines for the data sensing (Kim et al., 2007). However, due to the large number of nodes, non-determinism and noise, it might be extremely hard to guarantee real-time properties.
- *Security:* WSNs can be used in safety critical applications, thus their security is an essential issue to be considered. Denial of Service techniques can be easily executed over a WSN. Moreover, coordination and real time communication approaches do not consider security issues. Thus, some intruder can easily exploit these WSN security faults. The great dilemma is how to implement security techniques that need large computational resources in a technology that deals with severe hardware constraints.

In this scenario, where nodes are likely to operate on limited resources, power conservation is considered one of the most important concerns of these networks and different strategies and protocols need are adopted in order to deal with it (Gholamzadeh & Nabovati, 2008). In more detail, network lifetime can be enhanced if the system's software, including different layers and protocols, is designed in a way that lowers the consumption of energy (Gholamzadeh & Nabovati, 2008). Several techniques have been proposed in literature in order to decrease the power consumption of WSNs. These techniques are related to different aspects of sensor networks, from hardware platform to Medium Access Control (MAC) protocol, routing and topology control.

This Chapter is structured as follows: Section 2 summarizes the main applications where WSNs are deployed and their hardware characteristics. In Section 3, the main MAC layer approaches proposed in literature are described. Section 4 presents the routing strategies proposed in order to provide power optimization and consequently increasing WSN's lifetime, while Section 5 introduces Transmission Power Control approaches. Section 6 introduces Autonomic approaches and finally, in Section 6 the final remarks on the optimization of WSNs are presented.

2. WSN applications and hardware characteristics

WSNs are considered an application oriented technology, thus approaches that are developed for some specific application usually cannot be used for different uses. Important points related to the hardware characteristics of the nodes must be considered in order to guarantee the suitable node for a specific application. In more detail, aspects related to the type of processing unit as well as communication, power supply and sensing devices must be considered, when the nodes for a specific application are defined.

Considering aspects related to the processing unit, usually a microcontroller or microprocessor is adopted. In order to choose the ideal microcontroller for the system and due to the fact that microcontrollers with high performance imply higher power consumption, the designer must consider the desired performance level. Another important point is associated to the fact that microcontrollers usually support different operational modes, such as active, idle and sleep mode, which directly affect the power consumption of the node. There is also an attractive design option that suggests splitting the workload between two low power microcontrollers in such way that one of the microcontrollers is responsible for the sensing control, while the other performs the networking tasks related to controlling the RF interface and running the algorithms (Chou & Park, 2005). Finally, techniques like the one called Dynamic Volta Scaling (DVS) can be adopted (Karl & Willig, 2005). DVS dynamically adapts the microcontroller's power supply voltage and operating frequency to meet the processing requirement, thus trading off performance and power supply for energy savings.

Different communication devices using mediums like radio frequency or optical communications, for example, can be adopted to exchange data between nodes. For communication, both a transceiver and a receiver are required for the sensor nodes. The essential task of these devices is to convert a bit stream coming from a microcontroller into radio waves and vice versa. In more detail, the transceiver is normally regarded the largest power consumer and optimizing its power can result in significant improvement for the system as a whole (Chou & Park, 2005). There are several factors that affect the power consumption characteristics of a transceiver, including its type of modulation scheme, data rate, transmission power and the operational duty cycle (Gholamzadeh & Nabovati, 2008). Many transceivers allow the user to set the power level. In general, transceivers can operate in the following distinct modes of operation: Transmit, Receive, Idle and Sleep; allowing switching between them and consequently realizing energy savings. Note that the switching between the operating modes has to be managed, taking into account the fact that waking up a transceiver from the Sleep mode and making it go to Transmit mode requires some start-up time and start-up energy. Thus, switching a node into Sleep mode is only beneficial, if the energy necessary for the node to comeback into an active mode is smaller than the energy saved during the Sleep mode, which implies that the time to the next event is sufficiently large.

Regarding the power supply device, a battery is used in most of the cases, playing a vital role in determining the sensor node's lifetime. Thus, one of the most important factors that a designer must consider is the rate capacity effect, which is related to the discharge rate or

the amount of current draw from the battery. Drawing higher current than the rated value leads to a significant reduction in battery life, due to the fact that the diffusion of electrolyte falls behind the rate at which they are consumed at the electrodes. It is important to highlight that most of the applications of WSNs involve deploying sensor nodes in harsh and remote environment and therefore it is difficult to use ordinary recharging schemes for batteries. In particular cases, an alternative is to adopt external energy resources like sunlight or wind.

Finally, sensors in WSNs translate physical phenomena to electrical signals and can be classified as analog or digital devices depending on the type of output they produce. Basically, there are several sources of power consumption in a sensor: signal sampling and conversion of physical signals to electrical ones, signal conditioning, and analog to digital conversion (Gholamzadeh & Nabovati, 2008). Passive sensors, such as temperature sensors, consume less power than active sensors, like sonar, which need energy to send out a signal to probe the observed object. Indeed, the sampling rate is important and higher frequency sampling requires more energy. In this context, sensors should acquire a measurement sample only if needed, when needed, where needed and with the right level of fidelity (Raghunathan et al., 2006). This strategy reduces the energy consumed in the subsystem and sometimes reduces the processing and communication load as well. Thus, the use of mechanisms able to change the bit resolution of measurement samples and the sampling rate as well as using adaptive spatiotemporal sampling, exploiting redundancy and correlations models to predict a measurement instead of actually making it and finally, hierarchical sensing, can provide power consumption optimization.

In the next paragraphs, several WSN applications will be briefly presented. According to the temporal requirements of the applications, they may present significant differences in the applied algorithmic solutions. For instance, an environment monitoring application can require deadlines of minutes, while in a military application temporal validity is much smaller. Some kinds of applications need periodic sensing and sending, while other applications need an event driven approach.

Possible applications of WSNs include environment monitoring, military, domotic and industrial monitoring and control. For instance, an application of habitat monitoring is presented in (Mainwaring et al., 2002). The presented WSN has been deployed on the Great Duck Island. Its main goal is to correlate the measurements of some microclimate data (temperature, light and humidity) with the bird nest activity on the island. This application presents relaxed real-time requirements, thus the main goal of the Great Duck Island application is the maximization of the network's lifetime, as it is expected that the WSN's infrastructure stays active during months or even years without human intervention. Therefore, the intervals between sending messages and between one sensing and another may be reduced significantly.

Another example for a WSN's application is structural monitoring, in this case a linear WSN topology was used to monitor the Golden Gate Bridge's structure, and thus a routing technique had to be applied to assure the messages delivery to the BS at one end of the

construction. This application is based on accelerometer sensors that detect modifications in the physical structure of the bridge (Kim, S. et al., 2007).

Finally, other kinds of WSNs' utilization are stated below:

- *Automotive industry:* Cars are equipped with sensor and actor networks, which can interact with highway or street WSN infrastructures in order to increase traffic efficiency or automate toll payment;
- *Monitoring and automation of factory systems:* Industrial robots can be equipped with thousands of wired sensors. These sensors must be connected to a central computer. The high economic cost and the mobility restrictions of wired sensor are favour the utilization of WSNs in this kind of robots.
- *Intelligent housing:* WSNs permit that houses can be equipped with movement, light and temperature sensors, microphones used for voice activation and pressure sensors in chairs are also examples of WSN utilization in building automation. Thus, air temperature, natural and artificial lighting and other components can be tuned according to specific user needs;
- *Merchandise tracking:* Logistic and transportation companies may use WSN technology in order to track ships, transporters, containers or single goods that are being transported;
- *Precision agriculture:* Irrigation control and precise pesticide application are possible with the help of WSN utilization on farmlands;
- *Harsh area monitoring:* Exploration and monitoring of harsh areas may be possible throughout the use of WSNs;
- *Freshwater quality monitoring:* WSNs may be used for freshwater monitoring due to their non-intrusiveness and small size;
- *Military application:* Position and movement control of troops and vehicles, target detection, non-human combat-area monitoring as well as landmine removal or building exploration are just some examples of possible utilizations of WSNs for military applications.

To conclude, WSNs can be applied in different types of applications and the selection of the suitable hardware depends on the systems' requirements, the available resources and the environment where the network should operate.

3. MAC layer approaches

As previously mentioned, the lifetime maximization of WSNs is one of the most important concerns when dealing with the use of WSNs. This is mainly related to the fact that sensor nodes are considered unavailable when the battery level is depleted. In this context, it is important to note that communication among nodes is the major energy consumer process in WSNs. A significant portion of the node's energy is spent on radio transmissions and on listening to the medium for anticipated packet reception (Gholamzadeh & Nabovati, 2008). In other words, sending or receiving messages requires significantly more energy than data

processing or the acquisition by the sensors. Moreover, a single medium for communication is shared by the nodes and network performance largely depends on how efficiently and fairly these nodes share the medium. MAC protocol controls the communication nodes in WSNs and regulates access to the shared wireless medium such that the performance requirements of the underlying applications are satisfied (Sohraby et al., 2007). Thus, a careful definition of protocols and algorithms for efficient communication has become one of the most important issues in WSNs in order to improve their lifetime. Basically, the MAC protocol must be energy efficient and must try to reduce the following issues related to energy consumption phenomena (Demirkol, 2006):

- *Packet collision*: When one node receives more than one packet at the same instant, it is considered that a packet collision occurred. Therefore, all packets must be discarded and transmitted again.
- *Overhearing*: When some node receives packets that are addressed to another sensor node overhearing occurred;
- *Control packet overhead*: The use of control packets in order to coordinate the WSN must be minimized;
- *Idle listening*: Idle listening occurs when some node is in the listening mode of a channel that is not being used.
- *Over-emitting*: Over-emitting is caused when the message delivery fails due to the destination node's inactivity.

It is important to highlight that the collisions of messages is considered the most critical aspect, which causes the discarding of all involved messages and forces the network to retransmit increasing its energy consumption. Thus, an energy-efficient MAC protocol must avoid collisions and reduces the energy dissipation related to idle channel sensing, overhearing and overhead to a minimum (Ilyas & Mahgoub, 2005).

Regarding the types of communication patterns, four different types can be identified for WSNs (Demirkol, 2006):

- *Broadcast*: Generally BSs use the broadcast communication pattern (sink) to transmit certain information to all nodes under its controls. The broadcast information must contain consults, software upgrades or some control packet. The broadcast pattern can only be used, when all destination nodes are inside the radio coverage of the transmitter node;
- *Local gossip*: Local gossip is to be considered when nodes sense some event and send it to other nodes that are located inside the same location (same cluster). This kind of communication occurs when one node sends its messages to its neighbours, inside the same coverage area;
- *Convergecast*: This type of pattern is used when a group of sensors sends their packets to a specific node. The destination node can be a cluster-head, a fusion centre or a BS;
- *Multicast*: Some scenarios imply that messages need to be sent to a group of sensor nodes, thus just the sensors that belong to this group receive the message.

In the next subsection the IEEE 802.15.4 Standard and the ZigBee technology are described and the main MAC approaches able to reduce power consumption are summarized as well. Another subsection, will present further MAC approaches aiming at the optimization of MSNs.

3.1. IEEE 802.15.4 standard and the ZigBee technology

The main goal of the ZigBee technology is to enable WSNs composed of large number of nodes to function with reduced energy consumption. Most WSN technologies like *Mica Motes* use ZigBee in order to achieve higher lifetime levels for their WSN applications.

The ZigBee network architecture is based on the *Open Systems Interconnection* (OSI), however exclusively the more important layers were implemented. ZigBee adopts the IEEE 802.15.4 standard, which only defines the lower layers: the physical layer and the MAC layer (ZigBee, 2010).

The physical layer may operate on two frequencies 868/915MHz or 2.4GHz, with 16 channels and 250Kbps of maximum transmission rate. The IEEE 802.15.4 MAC layer is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. Note that ZigBee technology differs from other wireless technologies due to several reasons: lower data transmission rate, lower energy consumption, lower cost, higher self organization and more flexible network topologies (ZigBee, 2010).

The IEEE 802.15.4 standard has been proposed in 2003 and has become a *de facto* standard for low energy consumption and low data rate transmission networks. The IEEE 802.15.4 MAC protocol supports two kinds of operational modes that can be selected by a central node called Personal Area Network (PAN) coordinator. The two modes are:

- *Beaconless mode*: where MAC protocol functions are based on a CSMA/CA without beacon packet;
- *Beacon mode*: where beacons are periodically sent by the PAN coordinator in order to synchronize nodes that are associated with it and to delimit a *superframe. D*uring the *superframe* duration all node transmission must occur. Moreover, during the contention period of this frame the MAC protocol is ruled by the slotted CSMA/CA. The IEEE 802.15.4 with beacon mode can use the synchronization and the contention free period that is based on a guaranteed slot time.

Thus, the ZigBee Alliance is responsible for the ZigBee technology standardization. In more detail, the application and network layers are defined by the ZigBee Alliance itself, while the physical and MAC layers are based on the IEEE 802.15.4 standard. ZigBee may also consider time synchronization according to an optional *superframe* structure; the ZigBee technology possesses an address scheme that can handle up to 65.000 nodes. Moreover, three kinds of topologies are supported: *star*, *mesh* and *cluster tree*. The *Star* topology is considered the simplest topology and is based on a many-to-one communication topology, which means that all nodes are covered by the PAN coordinator antenna, and are able to send the messages in just one hop.

However, the *mesh* and *cluster tree* topologies rely on a routing protocol in order to deliver the messages to the PAN coordinator. *Mesh* topology does not allow cluster-heads and nodes to communicate with each other. Still different, the *cluster tree* topology is based on the organization of nodes into clusters. Basically, the *star* topology is considered simpler than the *mesh* and *cluster-tree* ones due to the fact that no routing protocol is necessary (ZigBee, 2010).

IEEE 802.15.4 standard is based on CSMA/CA MAC algorithm, its beaconless mode does not impose the sending of a periodical beacon by the PAN coordinator (IEEE 802.15.4, 2008).

Two parameters are considered in the beaconless mode: the first is denominated NB that is the Number of times CSMA/CA is required to backoff, the second is called Backoff Exponent (BE), standing for the number of backoff periods a device must wait until it can access the communication channel.

The first step of the CSMA/CA algorithm is the initialization of NB and BE. After the initialization, the MAC layer must wait a random period of 0 to $(2^{BE} - 1)$ and then require the Clear Channel Assessment (CCA) from the physical layer. When the channel is considered occupied by other device, the NB and BE is incremented by 1 by the MAC layer, though the MAC algorithm must guarantee that BE never grows above *macMaxBE*. Moreover, when NB´s value is above *macMaxCSMABackoffs*, the CSMA/CA algorithm must quit and returns the access channel failure status.

Finally, the Beaconless CSMA/CA algorithm is sensitive to three parameters: *macMaxBe* (standard value 5), *macMaxCSMABackoffs* (standard value 4) and *macMinBE* (standard value 3). These standard values for the parameters may help to decrease energy consumption due to the fact that devices try to send just five times before the transmission's abortion, however incrementing these values tends to increase the network's communication efficiency. Thus, the IEEE 802.15.4 protocol is not able to deal with dense network topologies, them being networks that are based on a large number of nodes.

3.2. Other MAC approaches

Several other MAC approaches have been proposed in literature in order to provide the reduction of power consumption in WSNs. In the next paragraphs the main solutions that explore the optimization of MAC protocols are summarized.

Techniques used in the MAC layer of WSNs often involve the use of Time Division Multiple Access (TDMA) and Duty Cycles (DC).

The main idea behind the TDMA technique is to divide the time spent by devices over channel accesses into so called time slots, each one used exclusively by one device. Therefore, by applying this technique, every device, before sending any messages, needs to book such a slot of time in advance. A TDMA MAC protocol is proposed in (Shi & Fapojuwo, 2010). This technique is based on a cross-layer optimization involving MAC and physical layers. The main goal of the presented technique is to reduce the overall energy consumption based on a TDMA scheduling with the shortest frame length for clustered WSNs.

In order to also reduce energy consumption, the TDMA MAC protocol is used in (Wu, Y. et al., 2010). Here, the main focus is to schedule the sensor nodes with consecutive time slots at different radio states, such as: transmitting, receiving, listening, sleeping, and idle. Due to the fact that sensor nodes consume different levels of energy at each state the optimum scheduling of these states could achieve the reduction of energy consumption.

FlexiTP is a TDMA MAC protocol that schedules node messages based on the so-called sleep scheduling approach (Lee et al., 2008). The sleeping scheduling scheme requires that sensor nodes to exclusively transmit and receive packets at their own time slot and turn into sleep state until their slot's turn is up again. FlexiTP also provides routing, time synchronization tasks and sensor nodes may sense as well as route data.

PEDAMACS is another TDMA MAC protocol designed for multihop WSNs (Ergen and Varaiya, 2006). It can improve the network's lifetime by several years when compared to other MAC protocols such as random access protocols that may reach months or just days of network lifetime. However, this TDMA protocol does not present a good performance when applied to WSNs with dynamic topologies, as they are common in harsh environments.

Complementarily, the DC technique divides the operating time of devices in two periods: active and inactive, also denominated sleeping time. The shorter the period of activity is in comparison with the period of inactivity, the longer the devices remains inactive and consequently achieves greater energy savings. As downside, a consequent reduction of the maximum transmission rate in the network is to be observed. If, on the one hand, TDMA enables devices to become more organized in order to avoid collisions; on the other hand, the DC technique is able to avoid cases where a node becomes simultaneously active with other nodes that had been inactive before, preventing a node to wait for messages that will never arrive, and finally avoiding the waste of energy.

These techniques generally allow the protocols to deal with collision, idle listening and over-emitting problems, but have overheads associated to sending and processing of control messages. Such extra-costs can be unnecessary in applications where the density of the network is small and where few devices transmit simultaneously. In this scenario, contention-based protocols such as Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) seem to be more suitable. Note that the CSMA/CA MAC protocol present in the IEEE 802.15.4 standard (IEEE 802.15.4, 2008) is inefficient for large networks.

A Rotational Listening Strategy (RLS) for Wireless Body Network (WBN) is presented in (Tseng et al., 2011). WBNs are a special kind of WSNs that are deployed over a human body area in order to sense and transmit scalars as for example the body's temperature. The RLS approach is based on the division of channel access partitioning it into mini-slots that are allocated to nodes.

Another type of WBN application is presented in (Omeni et al., 2008), where a MAC protocol implemented in hardware by a 0.13◎m CMOS process is described. In order to avoid collisions with nearby transmitters in a wireless body network, a standard listen-before-transmit technique is being used. The time slot overlap handling was reduced based on a wakeup-fallback approach.

A different Wireless Body Networks (WBN) MAC protocol is proposed in (Otal et al., 2009). The main goal of this MAC protocol is the maximization of the battery lifetime of each individual body sensors while maintaining the reliability and message latency of data transmissions at the same level. To do so this MAC protocol is based on a cross-layer fuzzy rule scheduling algorithm and a energy-aware radio activation policy for realistic medical applications.

An Energy-Aware Hybrid Data Aggregation (EDHDAM) technique is presented in (Kim, M. et al., 2011). It aims at minimizing the energy problem in asynchronous MAC-based WSNs. The nodes closer to the sink spend more energy than other, this is due to the fact that they receive and send more data to the WSN's sink then nodes that are far away from the sink. Thus, the EDHDAM technique is designed to adaptively control the number of data transmissions in order to avoid the before mentioned downside.

A game-theoretic MAC approach for WSNs is presented in (Zhao et al., 2009). The MAC of nodes in this technique is based on an incompletely cooperative game mode. This approach denominated G-MAC, where time is divided into super-frames, each super-frame having two parts: an active part and a sleeping part. During the sleeping part, all nodes turn-off their radios to save energy and during the active part, if some node has packets to send, these will pass on the channel that is based on the incompletely cooperative game.

Multiple cross-layer protocols that integrate MAC and WSN's network layers are presented in (Rossi & Zorzi). All these MAC protocols are cost-aware regarding residual energies, link conditions, and queue state. The routing layer chooses the best relay candidates based on the MAC protocol information. In this manner, the number of in-range devices, that compete for one channel as well as the interference are reduced.

A technique named S-MAC, a medium access control based on coordinated adaptive sleep scheduling, is presented in (Ye at al, 2004). S-MAC tries to avoid the overhearing problem by low-duty-cycle operations in a multi-hop WSN. The S-MAC approach organizes the sensor nodes into virtual clusters based on common sleep scheduling in order to reduce the control overhead and enable traffic-adaptive wake-ups.

Finally, MRMAC is a MAC protocol that reduces the end-to-end delay as well as the energy consumption in WSNs. The approach presented in (Hong *et al.,* 2010) reduces the end-to-end delay based on two metrics: Next Packet Arrival Time (NPAT) and Medium Reservation Information (MRI). When a sender transmits a packet, the NPAT and MRI metrics are enclosed in the packet in order to make possible that its intended receiver reserves the medium. The simulations presented by show that the MRMAC approach is able to significantly reduce, both end-to-end delay and energy consumption.

4. Routing approaches

WSNs can be adopted for a wide range of applications, but in all of them, the main task of the nodes is to sense and collect data, process it and transmit the information to the site where it is possible to analyse the monitored parameters. To efficiently achieve this task, it is

required the development of an energy efficient routing protocol to set up paths between the nodes and the data sink (Sohraby et al., 2007). Due to the fact that sensor nodes are energy constrained, great part of the WSN's protocols aim at minimizing the energy required for communications. Basically, the environment characteristics coupled with scarce resources and energy limitation make the routing problem very challenging. Thus, the path selection must be such that the lifetime of the network is maximized. In this context, different strategies can be adopted in order to face with this problem. One simple strategy is to avoid bad-quality routes because unreliability of wireless links has an adverse effect on their performance. Link failures and packet losses lead to many retransmissions and therefore, result in higher power consumption.

A clustering protocol called REACA is presented in (Quan et al., 2007). REACA's functioning is divided into two cycles: the first cycle is dedicated to the network configuration while the second cycle handles the message transmission. The cluster-head to be chosen is based on the battery level of all nodes that compose the cluster. Thus, the node that presents the highest battery energy level is chosen to function as cluster-head. Moreover, a routing algorithm is proposed and REACA is validated by mathematical analysis.

EARQ by (Heo et al., 2009) is a routing protocol based on the WSN's energy level. EARQ is able to guarantee dependability, temporal constraints and energy economy. The main goal of EARQ is to use the path with the greatest energy level inside a WSN. Its authors prove by simulations that EARQ may be implemented in a WSN for industrial application. However, EARQ was not validated for any WSN prototype. Another cluster-tree WSN routing protocol was proposed by (Alippi et al., 2009).

The approach called MMSPEED is a routing protocol that is able to guarantee probabilistic Quality of Service (QoS) metrics in WSNs. It was proposed by (Felemban et al., 2006), considers different options of speed delivery in the time domain and guarantees package delivery. Several dependability requirements are provided, which are based on several path options. The end-to-end requirements are provided in a located fashion; this is desirable in terms of scalability and adaptability in dynamic and dense WSNs. However, the utilization of geographical routing imposes that nodes need to know their geographical localization. Thus, the proposing authors considered that each node would possess GPS devices or distributed localization algorithms. This results in considerable problems, as GPS devices do not work properly in indoor environments and distributed localization algorithms impose an extra overhead due to the extra package exchange, since the nodes need to periodically broadcast their geographical localization.

The q-Switch, a simple path routing algorithm proposed in (Wu, X. et al., 2008), is a routing technique used to support the non-uniform node distribution strategy that is used to mitigate the energy hole problem in WSNs. Its authors also show that in a circular multi-hop WSN with non-uniform node distribution and constant data sending the unbalanced energy consumption is unavoidable.

An approach denominated the Energy Efficient Broadcast Problem (EEBP) in ad hoc wireless networks is presented in (Li et al., 2004). The EEBP's idea can be described by the following phrase: in a given an ad hoc wireless network, find a broadcast tree such that the energy cost of the broadcast tree is minimized. Its authors consider that all the network´s nodes present a fixed level of transmission power. As solution three routing approaches aiming at the minimization of the network´s consumption are proposed.

A sleep scheduling solution called Green Wave Sleep Scheduling (GWSS), which has been inspired by synchronized traffic lights, is presented in (Guha et al., 2011). The main goal of this approach is to support the WSN´s routing duty cycling. A green wave is a moving sequence of consecutive active states (green lights), and some packet may move in a sequence of active nodes. Thus, nodes in sleep mode are compared to red lights, and packages may not be routed through a sleeping node. Its authors show that, considering large WSNs arranged in structured topologies, GWSS achieves almost the same end-to-end latency as that of non-sleep-scheduling WSNs.

5. Transmission power control approaches

Power conservation is so important because nodes are usually operating on limited batteries. As previously mentioned, MAC protocols are able to manage energy consumption during WSN communication, which is the most energy-consuming event in WSNs. However, one interesting solution in order to increase WSN's lifetime is based on adjusting its nodes' transmission power. On the one hand, maintaining the lowest possible transmission power represents a interesting solution in order to minimize the energy consumption and consequently increase the network's lifetime. On the other hand, the lowest possible transmission power can increase the WSN's vulnerability to the interference fluctuations caused by bad Signal-to-Interference-plus-Noise-Ratio (SINR) (Kim & Know, 2008). Extensive empirical studies confirm that the radio communication's quality between low power sensor devices varies significantly with time and environment. This phenomenon indicates that the existing topology control solutions, which use static transmission power, transmission range and link quality, might not be effective in the physical world (Lin et al., 2006). In this context, online transmission power control techniques that take into account environment variations have become essential in order to address this issue.

Several Transmission Power Control (TPC) approaches have been proposed in the literature. Basically, the TPC algorithm can reduce the energy consumption and improve the channel capacity. In more detail, TPC solutions use a single transmission power for the whole network, not making full use of the configurable transmission power provided by radio hardware to reduce energy consumption or assume that each node chooses a single transmission power for all the neighbours, which is know as neighbour-level solutions. Indeed, most existing WSNs use a network-level transmission power for each node.

There are many TPC studies, which mainly focus on improving the channel capacity (Monks et al., 2001; Ho & Liew, 2007). Recently, experimental studies (Don et al., 2004)(Lin et al., 2006) have shown that TPC reduces energy consumption in low-power WSNs. In Power Control Algorithm with Backlisting (PCBL), each node sends packets at different transmission power levels to determine the optimal transmission power based on the Packet Reception Ration (PRR). In (Lin et al., 2006), an Adaptive Transmission Power Control (ATPC) algorithm is proposed in order to achieve the optimal transmission power consumption for specified link qualities. Employing a ATPC algorithm, the Received Signal Strength (RSS) and the Link Quality Indicator (LQI) for radio channels are used to estimate the optimal transmission power level, and employ a feedback-based ATPC algorithm to dynamically adjust the transmission power over time. Thus, the result of applying this algorithm is that every node knows the proper transmission power level to use for each of its neighbours and every node maintains good link qualities with its neighbours by dynamically adjusting the transmission power through on-demand feedback packets.

However, the effect produced by different inference sources must be considered when the goal is the implementation of WSNs in the physical world. Many WSN devices available on the marked operate on the 2.4GHz ISM band and are vulnerable to the interferences from other wireless networks such as the IEEE 802.11 WLANs or the IEEE 802.15.1 Bluetooth (Kim & Know, 2008). Generally, the transmission power of the WSN devices is lower than that of WLAN or Bluetooth devices. Therefore, the TPC algorithm for WSNs has to carefully consider the interferences caused by other 2.4GHz wireless devices, which can cause significant performance degradation. In this context, a practical TPC algorithm for WSNs, named Interference Aware Transmission Power Control (I-TPC) algorithm has been proposed in (Kim & Know, 2008). The I-TPC algorithm is based on the idea that each node adjusts the RSS target to provide the acceptable SINR when interferences are detected. In more detail, the I-TPC algorithm consists of two functional procedures: the two-tier transmission power control and the RSS target adjustment. Initially, the proper RSS target, which may satisfy the desired PRR is determined. Based on this RSS target, each node tries to adjust its transmission power to keep the RSS value within the upper and the lower RSS target values by using the two-tier transmission power control procedure. The net effect of this operation is that the proposed algorithm tries to reach a satisfying link quality quickly even if there are small-scale link quality variations. When the interference is detected, the RSS target and the transmission power are increased immediately by the RSS target adjustment procedure to provide an appropriate SINR.

Two different local algorithms to individually adjust the nodes' transmission power are presented in (Kubish et al., 2003). Such local approaches do not require any particular MAC protocol or dedicated protocol for route discovery. The so-called Local Mean Algorithm (LMA) implements that each node periodically sends a *life message* and all receiving nodes respond with *life acknowledge messages.* Before sending new information each node counts the received acknowledge messages and compares this number to the value set as thresholds. In the case the node received less messages then the inferior threshold, the transmission power is increased by factor A_{inc} for every node missing to

achieve the threshold. If this number is in the range between the minimum and maximum threshold no changes to transmission power are made. Similarly, the Local Mean Number of Neighbours (LMN) algorithm works with life and life acknowledge messages. In addition to the LMA approach the *life acknowledge message* contains the nodes own count of neighbours. Thereby each node receives a number of messages containing a value indicating the numbers of neighbours of the sending node, then calculates a mean value from all the received messages and uses this value as well as the number of nodes that responded to its *life message* to calculate the so called *NodeResp* value to be compared with the thresholds and, if the case, the transmission power is adapted as described in the LMA technique. These two techniques are compared to fixed and global algorithms and, in the given indoor scenario, are outperforming the fixed approaches while reaching only about half the lifetime of networks employing global algorithms such as the Equal Transmission Power (ETP) algorithm. It is noted that comparing such approaches to ETP the local algorithms are almost competitive when looking at the network's confidence level and on top are scalable and easily implementable, which global algorithms are not.

Finally, a Transmission Power Self Optimization (TPSO) technique is presented in (Lavratti et al., 2012). It basically consists of an algorithm able to guarantee the connectivity as well as an equally high Quality of Service (QoS) concentrating on the WSN's Efficiency (*Ef*), while optimizing the necessary transmission for data communication in each node. The technique aims at adjusting each node to use the lowest possible transmission power while maintaining the connectivity to the WSN and the reliability of the network as a whole. This trade-off between the WSN's *Ef* and the data transmission energy consumption is evaluated in different EMI environments. Its decentralized algorithm runs on the application layer and uses an *Ef* value calculated, which adopts the number of received messages and the estimate of sent messages. This *Ef* is compared with the targeted *Ef* in order to decide about adjustments to the node's transmission power. Experimental results show that the automatic adaption presents advantages when compared with approaches using fixed transmission power. It is shown that the technique is able to guarantee the trade-off between *Ef* and power consumption. The TPSO behaviour is shown in Figure 1. It is possible to notice that the energy dissipated by a node with fixed transmission power is much higher than the energy consumed by a node running the TPSO algorithm. The session values in the x-axis represent the elapsed time.

Figure 2 shows the WSN's *Ef* and the WSN's energy consumption with respect to the WSN using the five pre-defined transmission power levels and to the WSN adopting the TPSO technique.

We can observe the effectiveness of the TPSO technique with respect to the use of pre-fixed transmission power levels. In detail, we can see this network using the maximum transmission power level reaches about 80% of *Ef*, but consumes about 50mW.s, while the WSN adopting the TPSO algorithm reaches the same *Ef* consuming only about 25 mW.s.

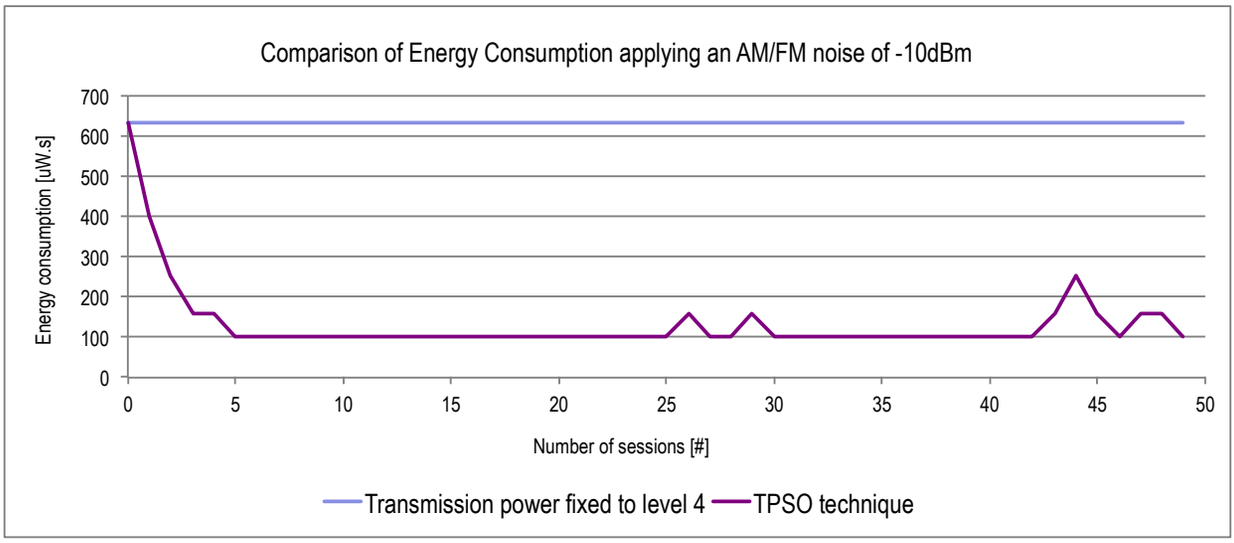

Figure 1. Comparison of the energy consumption of the TPSO technique with respect to WSN operating with the transmission power fixed to level 4 (Lavratti et al., 2012).

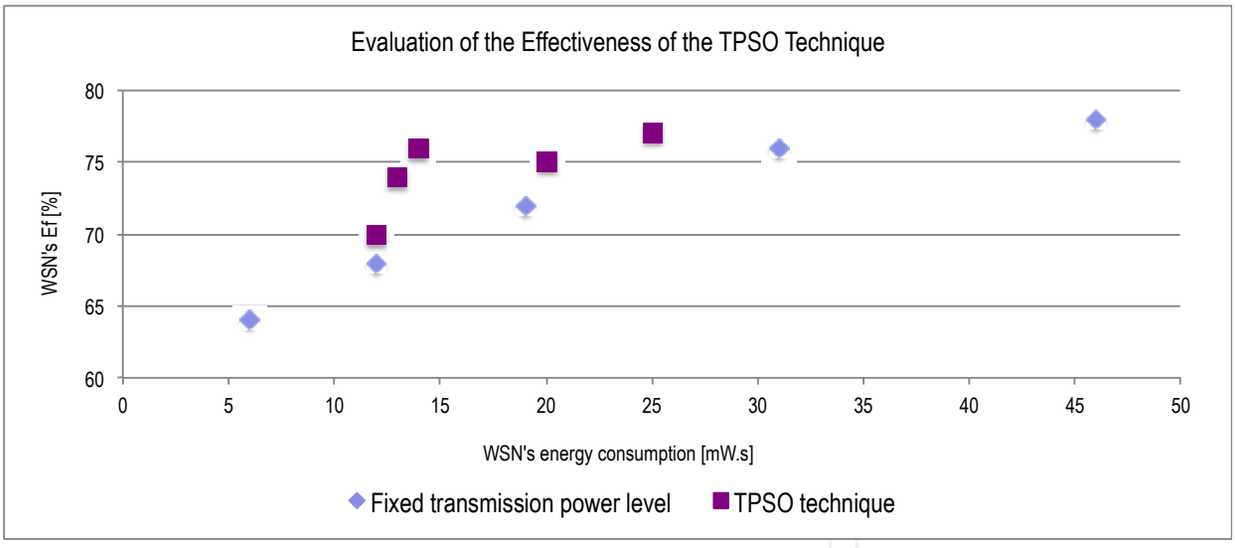

Figure 2. Evaluation of the TPSO technique with respect to WSN's Ef and energy consumption applying AM/FM noise of -14 dBm (Lavratti et al., 2012).

Figure 3 depicts the *Ef* of two WSNs, one with the transmission power level set to 0 and one with the TPSO technique. The WSN with the fixed transmission level is able to reach an average *Ef* of 46.4%, while the other network is achieving 86.6%. As the WSN with the TPSO technique is switching to higher transmission power levels to cope with the introduced noise it needs 253% more energy to reach the higher level of effectiveness.

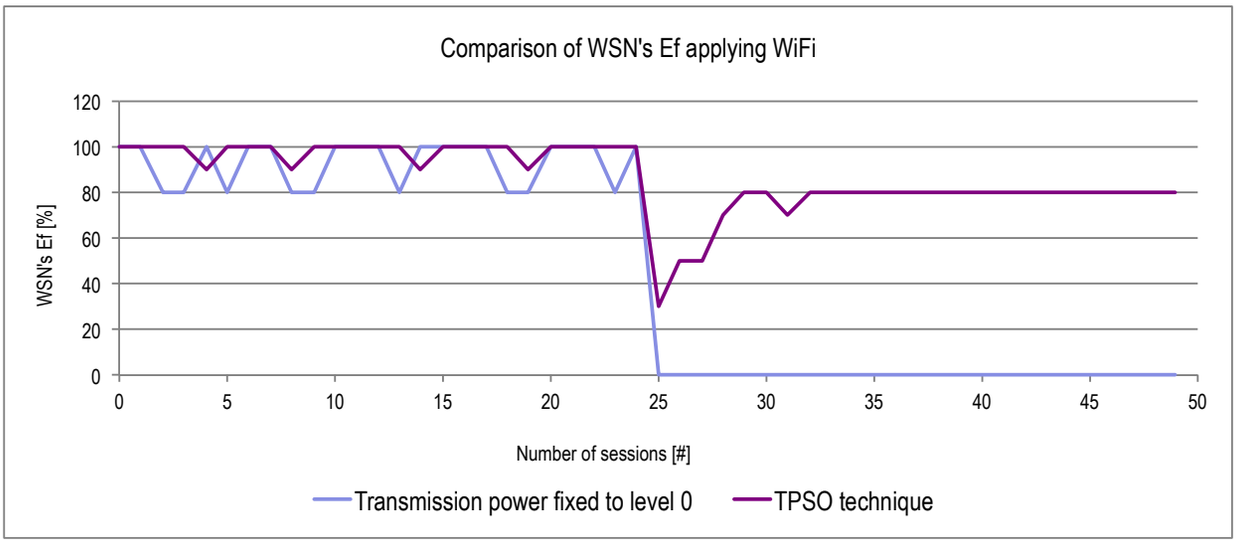

Figure 3. Comparison of the WSN's Ef of the TPSO technique with respect to WSN operating with the transmission power fixed to level 0 (Lavratti et al., 2012).

The results obtained during the experiments demonstrated the convenience of using the self-optimization algorithm instead of setting the maximum transmission power level. When a WSN without the TPSO technique is considered, the transmission power is set at the beginning of the communication and remains the same during its entire lifetime. This characteristic can be negative considering a WSN in a real environment where the inherent noise is not necessarily constant. Therefore, due to the fact that the inherent environment noise is completely variable and random, the TPSO technique will always guarantee the lowest possible transmission power during the communication and the target_*Ef* when it is possible (Lavratti et al., 2012).

6. Autonomic approaches

IBM introduced the term autonomic computing in 2001 to describe computer systems able to self-manage themselves (Kephart and Chess, 2003). The main properties of approaches categorized as "self-*" are:

- self-configuring
- self-optimizing
- self-healing
- self-protection.

Each one of them is described in (Huebscher and McCann, 2008). A brief definition is presented below:

- Self-configuration: the system's ability to configure itself according to high level goals;
- Self-optimization: the system can decide to start a change in the system as pro-active, in order to optimize the performance or quality of service;
- Self-healing: the system detects and diagnoses problems, which can be either faulty bits in a memory chip or a software error;
- Self-protection: the system is able to protect itself against malicious attacks or unauthorized changes.

Even though dense WSNs present several advantages, self-management characteristics are required in order to deal with the management of a large number of nodes. Self-management techniques are part of autonomic-computing methodologies, which can also be used to manage WSNs with conflicting targets (energy efficiency, self-organizing, time constraints and fault tolerance). The main goal of self-management is the development of a computing system that does not need the human intervention to operate. This way, computing systems are able to self-organize and self-optimize themselves, once they follow global objective dictated by a system administrator (Pinto e Montez, 2010).

For instance, in dense WSNs composed of several sensor nodes in a star network topology, in case the network presents conflicting goals (increase dependability and energy efficiency, while meeting time constraints), the conventional IEEE 802.15.4 protocol does not seem to be able to deal with the complexities. For example, when the number of nodes in a network is increased, in order to achieve better reliability the WPAN may be congested, and fewer messages arrive in the base station on time. In order to demonstrate the WSNs behaviour in this situation, experiments using TrueTime simulator[1] were performed. Two metrics called *Ef (efficiency)* and *QoF* have been adopted. While efficiency is a metric that measures the ratio between sent and received messages; *QoF* represents the average number of received messages by the base station over a certain timespan. Figure 4 shows that when density network is increased, QoF increases slowly, but communication efficiency quickly decreases.

(Pinto e Montez, 2010) propose a Genetic Machine Learning Algorithm (GMLA) aimed at applications that make use of trade-offs between different metrics. The main goal of the GMLA approach is to improve the communication efficiency, in a communication environment where the network topology is unknown to the base station.

Simulations were performed on random star topologies assuming different levels of faults. Observing Figure 5 it can be notice that the communication efficiency maintains the same level when IEEE 802.15.4 is used. However, when GMLA is used, it is possible to notice a gain of almost 10% in communication efficiency.

[1] freely available at http://www.control.lht.se/truetime.

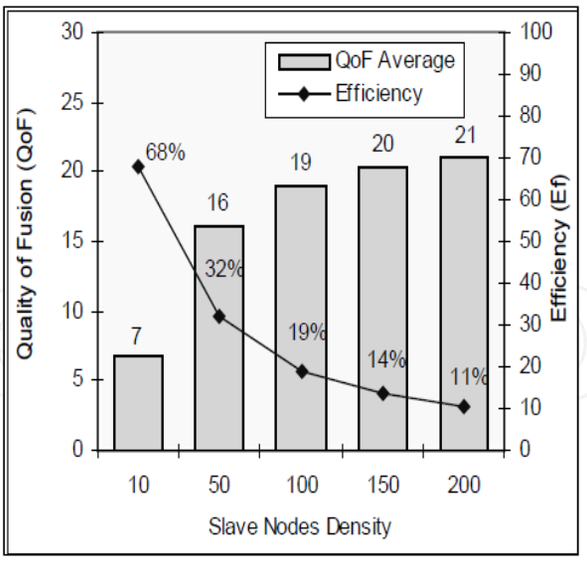

Figure 4. IEEE 802.15.4 simulated behaviour.

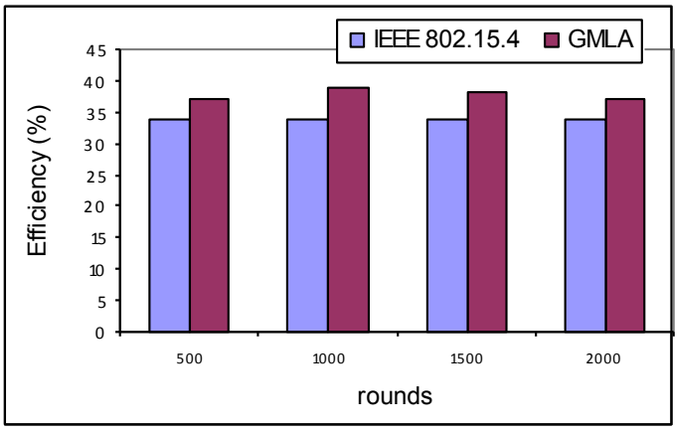

Figure 5. Comparison of GMLA and IEEE 802.15.4.

It is possible to notice that IEEE 802.15.4 presents a static behavior, and that it does not learn better communication patterns when topology changes are faced (Figure 6).

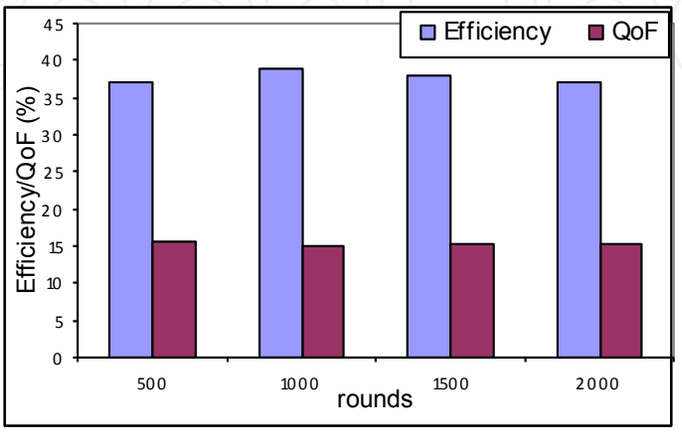

Figure 6. GMLA Efficiency and QoF values.

An analysis of Figure 7 indicates that the *QoF* is maintained at almost the same level, in all simulations. However, the higher level of *Ef* was achieved with 1,000 round simulations. This may be explained through GMLA´s learning behaviour, which tries different configurations when longer simulations are run.

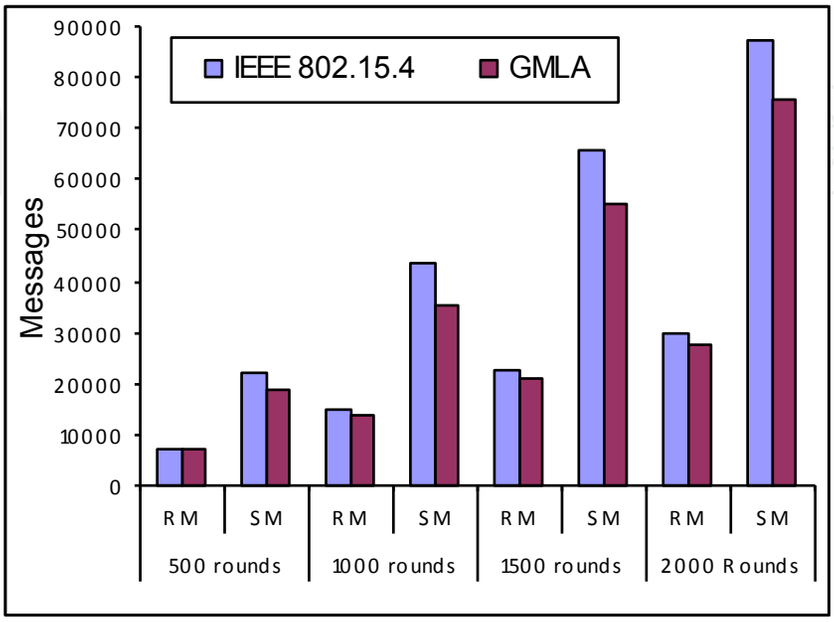

Figure 7. Sent (SM) and Received Messages (RM).

Consequently, it is possible to conclude that the GMLA approach is able to do the trade-off between *QoF* and *Ef* and GMLA uses lower levels of energy than IEEE 802.15.4. However, this approach is only suitable for applications with a homogeneous signal throughout the entire monitoring area.

Also in (Pinto e Montez, 2010), a Variable Offset Algorithm (VOA), which targets the optimization of the communication efficiency in dense WSNs with star topology, is proposed. The VOA can be easily implemented into IEEE 802.15.4 devices, as it is a light middleware that is implemented at the application layer. The main target of VOA is the communication efficiency through the use of random offsets before the transmission of data by the slave nodes.

The VOA algorithm was assessed with the help of an experimental setup based on real situations and one of the experiments has been performed by varying the number of slave nodes. The results are shown in Figure 8. The goal was to evaluate the influence of the number nodes on the *Ef* and *QoF* metrics. When compared with VOA, IEEE 802.15.4 presents similar results for just one case: a network with 4 slaves. When the number of slaves increases, the difference between VOA and IEEE 802.15.4 become greater. The difference of efficiency between VOA and IEEE 802.15.4 when considering 29 slaves is of more than 100%. These results show that VOA has a satisfactory performance and maintains a minimum QoS level even with a high number of slaves (Pinto e Montez, 2010).

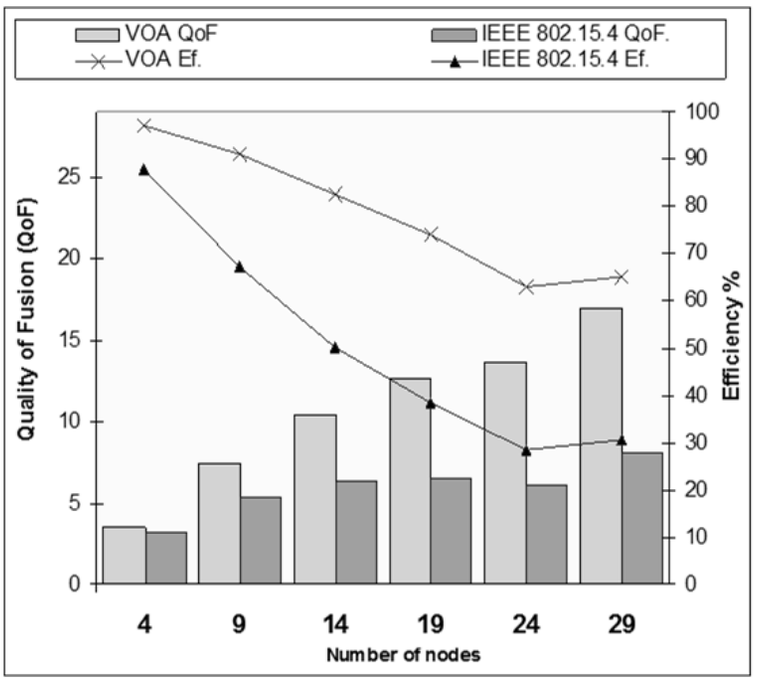

Figure 8. Comparison of VOA and IEEE 802.15.4 protocol with variable number of nodes.

The Decentralized Power-Aware Wireless Sensor Network (DPAWSN) approach has the main goal of maintaining a minimum *QoF*, while improving the *Ef* and saving energy. This approach can be considered as decentralized, due to the fact that nodes have autonomy to decide whether to send or not to send messages. On the one hand, a certain *QoF* level is imposed by network administrator, on the other hand, the WSN´s lifetime is increased by the power awareness decision taken in each node.

The main idea behind DPAWSN is that the base station will control each node in order to decreases or increases the transmission rate when the *QoF* level is above or below the target value. Thus, DPAWSN is able to maintain a *QoF* level and increase the WSN´s lifetime due to the fact that nodes present a selfish behaviour as the nodes transmission rate is calculated based on individual remaining voltage.

The test assessment was conducted in a noisy environment with an unspecified number of computers communicating using IEEE 802.11.

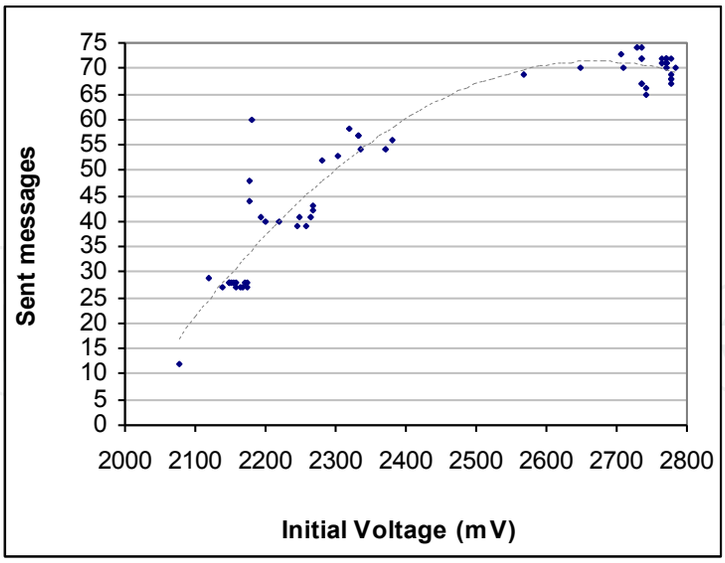

Figure 9. Figure. 9. Dispersion Graphic of 30 tests (each point represents sent messages of lower or higher battery level nodes).

Figure 9 shows the correlation between sent messages and the initial voltage in each node. Note that the initial value on the x-axis is 2000mV, which represents the minimum battery conditions for a node to work. It is possible to notice that two regions are present in the graph: the first one represents sent messages of nodes with a lower level of battery and the second one represents sent messages of nodes with a higher level of battery. In more detail, each point represents the average number of sent messages (y-axis) over the initial voltage average of the node (x-axis). The effectiveness of DPAWSN is confirmed by Figure 9, since lower battery level are applied to nodes that send less messages and nodes with higher battery level do send more messages.

Finally, DPAWSN is able to autonomically adjust the transmission rate based on the voltage level of the nodes. Moreover, it is able to achieve a targeted *QoF* imposed by system administrators.

7. Final considerations and future directions

WSNs represent one of the most interesting solutions to monitor and sense data in hazardous or inaccessible areas. This Chapter presented various possible approaches that designers might adopt in order to provide an energy efficient WSN. Due to the enormous variety of environments that these networks may be used in, numerous challenges and constraints have to be considered when choosing the optimization approach. Also, different goals and applications call for different targets that may not be achieved up to a satisfying level at the same time. Therefore, some approaches offer to define a trade-off between opposing aims, such as *QoS* and energy consumption. Each solution presented in this Chapter is aiming at solving at least one identified cause of extensive energy consumption. The approaches are using the WSN's different design levels to increase the network's lifetime, *QoS*, and/or optimize other points that may or may not suit the designer.

Taking into account that lifetime maximization is one of the main goals of WSN approaches, and as the WSN devices consume more energy during the transmission and reception of packets, even in short distances, than other tasks such as those related to processing, sensing and data storing, the design of efficient protocols and communication algorithms is a research direction.

The current tendency goes towards solutions that involve a trade-off between more than one constraint or that may adapt or change the behaviour of the WSN's nodes during its employment are showing that researches are aware of the complexity and unpredictability of the environment and task of such networks.

However, some existing research areas are becoming more relevant, mainly due to the recent technology evolution of these networks. For example, the most popular motes in the years 2000-1010 were based on 4 to 8 MHz processors and 128 Kbytes memory; but recently there are motes with 180MHz processor and up to 4Mbytes memory, supporting Java Virtual Machine. Therefore, the hardware evolution trend directs researches to implement more sophisticated and robust approaches in an autonomic and distributed way with multi-objective optimization approaches, however with power consumption as an important goal.

The gradual replacement of very expensive centralized sensor systems by a set of wireless sensor nodes, which operate in a collaborative and autonomic way (mainly with self-management and self-healing properties) is also becoming a trend. Thus, multi-agent approaches and lightweight optimization techniques are emerging as an alternative. This fact is mainly due to the distributed and optimized way that these approaches perform.

Moreover, the gradual increase in the motes´ local storage capacity has induced the use of WSN data mules. The respective research focuses on the development of architectures and algorithms where nodes must locally storage their sensed data until mobile nodes (mobile base stations) gather this information.

As final consideration it is to be stated that the variety of challenges has generated an even greater number of approaches to deal with the concerns that WSNs face in all the possible harsh and noisy environments they may face today. It is now the designers' task to find the best match or combination to optimize the network according to its environment, its tasks, and its most important requirements and constraints. As there is no solution that may cover all problems at the same time, the correct analysis of problems to be expected has become one of the most important parts of the work of today's designers.

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